eRHIC ring-ring Luminosity

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Topics

1. ZDR design goals
2. Beam-beam
3. Collective effects
4. Low energy operation
5. Summary and the luminosity sheet

1. eRHIC ZDR design luminosity goals

	e-p, e^+-p	e-p,e^+-p	e-Au, e^+-Au	e-Au, e^+-Au
Energy (GeV) Lepton/hadron	10/250	5/50	10/100	5/100
Longitudinal Polarization at IP	≥70% $e^\pm$ & p	~60% for e ≥ 70% for p	≥ 70% $e^\pm$	~60% e
Luminosity $\times 10^{32}$ $cm^{-2}s^{-1}$	4.4	1.5	0.044	0.02

eRHIC Luminosity Equation

Head on collisions, size matched elliptical e & p beams,

$\sigma_y < \sigma_x$

$$L = \frac{\pi}{r_e r_i} f_c \gamma_e \gamma_i \xi_e \xi_i \sigma'_{i,x} \sigma'_{e,x} k_e \frac{(1+k)^2}{k^2}$$

$$\xi_{i,x} = \frac{r_i}{2\pi Z} \frac{N_e}{\gamma_i \varepsilon_i} \frac{1}{(1+k)}$$

$$\xi_{e,y} = \frac{r_e Z}{2\pi} \frac{N_i}{\gamma_e \varepsilon_{e,x}} \frac{1}{k_e (1+1/k)}$$

with $\sigma'_{e,y} \leq \sigma'_{e,x}$

$\xi_{i,e}$: beam-beam tune shift limit for ion beam or electron beam.

β^* : β-function at IP, $\geq$19 cm.

ε: ion or electron beam geometric emittance.

$k_e = \varepsilon_{e,y}/\varepsilon_{e,x}$:electron beam emittance ratio, ~0.2.

$k=\sigma_y/\sigma_x$:beam aspect ratio at IP, ~0.5.

$\sigma_{i,x}'$: ion beam angular amplitude. $\sigma'_{i,x} \leq$ 93 urad is an aperture limit (IR design)

$\sigma_{e,y}'$: elecetron beam angular amplitude, not a real aperture limit.

$r_{i,e}$: classic ion or electron radius.

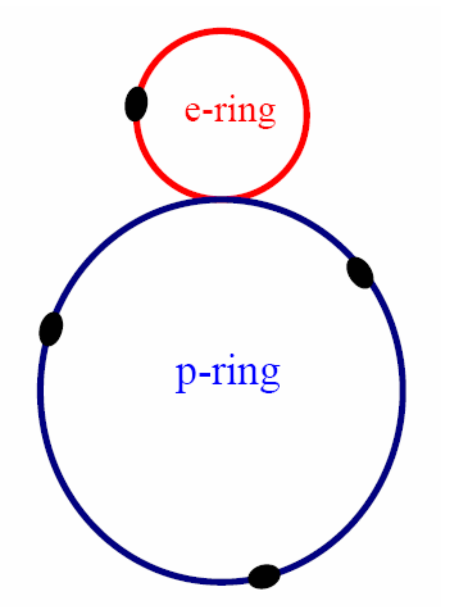
Z: ion atomic number

2. Beam-beam

➢Beam-beam limits ? ξ_e, ξ_i

•Lepton beam and hadron beam.

•Different operation scenarios.



➢Collider with unequal-circumference rings

Coherent b-b limit, enough stable region for operation ?

C. Montag
BNL/CAD

Strong-weak simulation

Examine: $\xi_{e,y}=0.08$

& $Q_1-(C_1/C_2)Q_2=n$

(**unequal-circumference rings**)

Simulations:

•One e bunch – three p bunches.

•Rigid Gaussian bunches.

•Tracking: 100 macro particles, ten damping time.

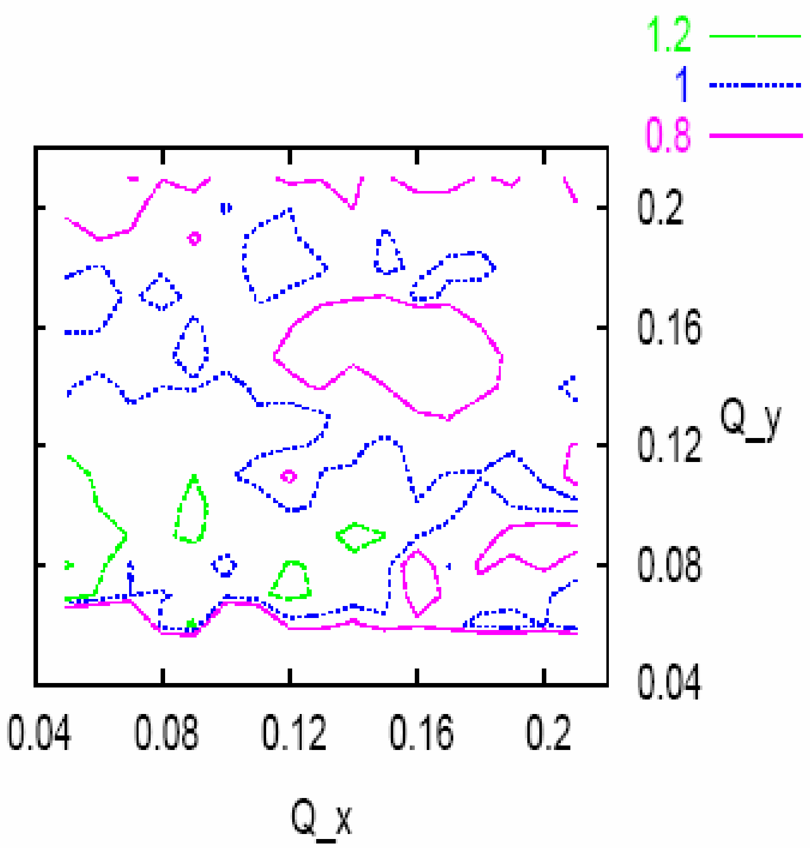
•Dynamic focusing, equilibrium emittance

Results:

▪Sufficient large area in the working diagram.

▪Unequal circumference not much of a concern.

▪Further investigation of working point (non Gaussian tails).



L/L_0 vs. Q_x, Q_y

J. Shi et al.
Univ. Kansas

Strong-strong simulation

Examine:

- **Beam-beam limits for both lepton and hadron beams**
- **Coherent beam-beam interaction limit (unequal circumference of the rings).**

Simulations:

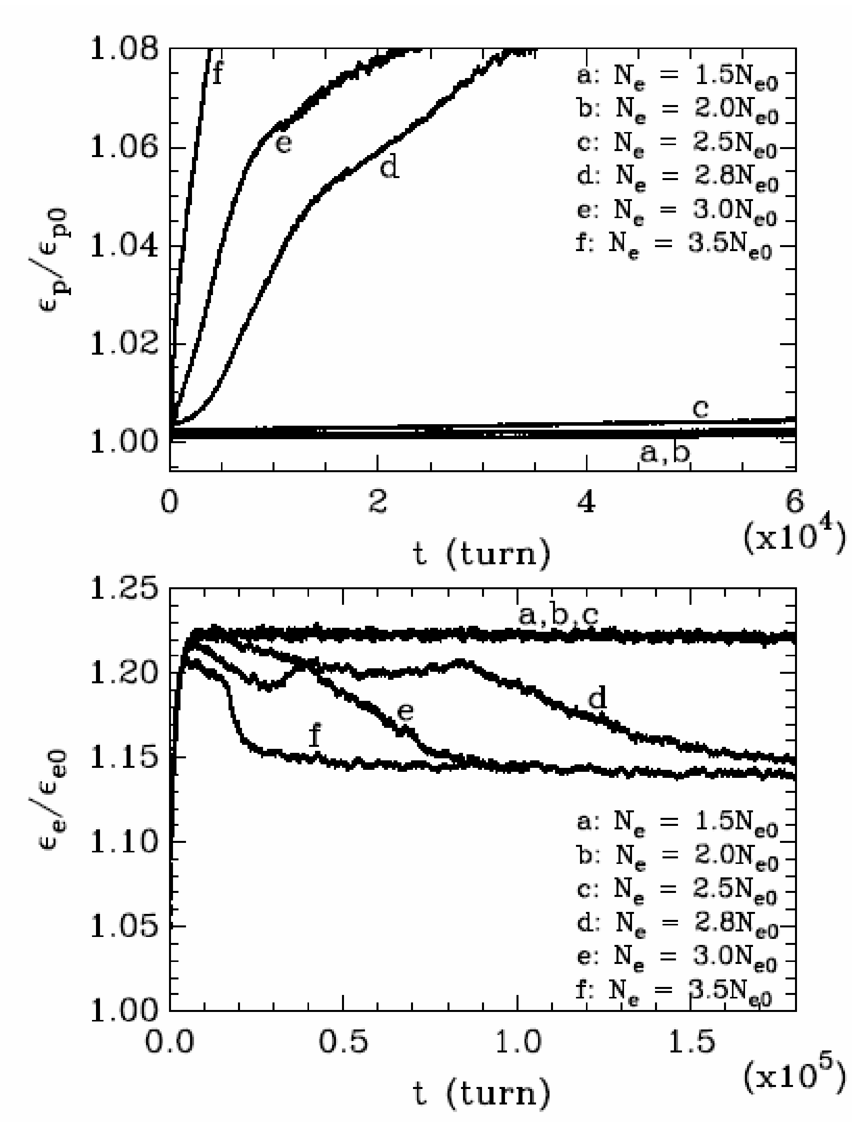
>Self-consistent.

>Particle-in-cell (PIC) method

5×10^5 macro particles / bunch.

>Beam-beam limits: **Examined as the thresholds of the onset of the coherent beam-beam instability.**

Beam-beam limit of the Proton beam



$(\nu_{e,x}, \nu_{e,y})$ = (26.104, 22.146)

$(\nu_{p,x}, \nu_{p,y})$ = (28.19, 29.18)

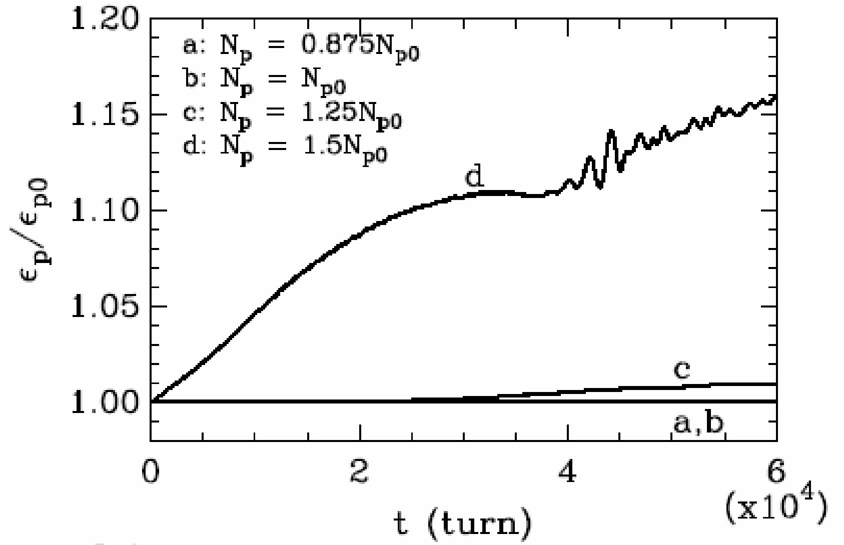
$N_e = 2.5N_0$

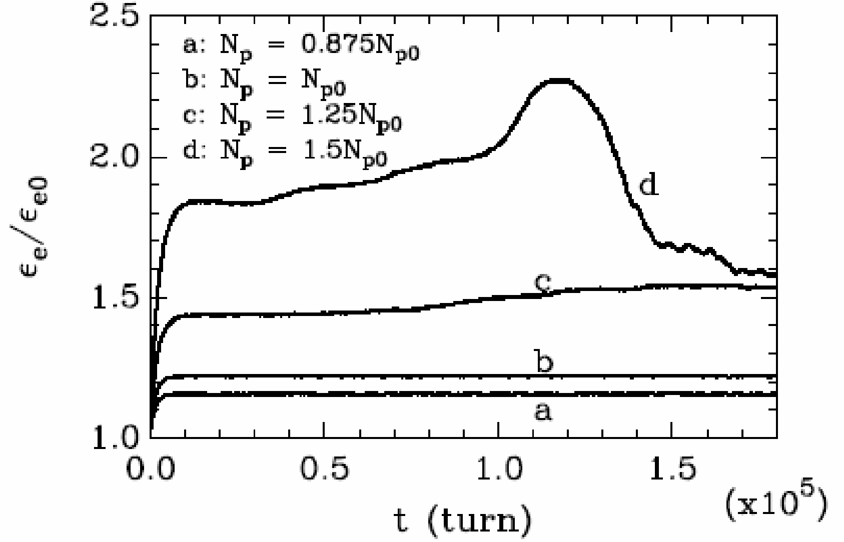
$I_e = 2.5*0.45A = 1.125$ A

ξ_p =2.5* , ξ_{p0} =0.016

Simulation suggests a higher proton b-b limit of .016 for single IP operation is achievable.

Beam-beam limit of the electron beam



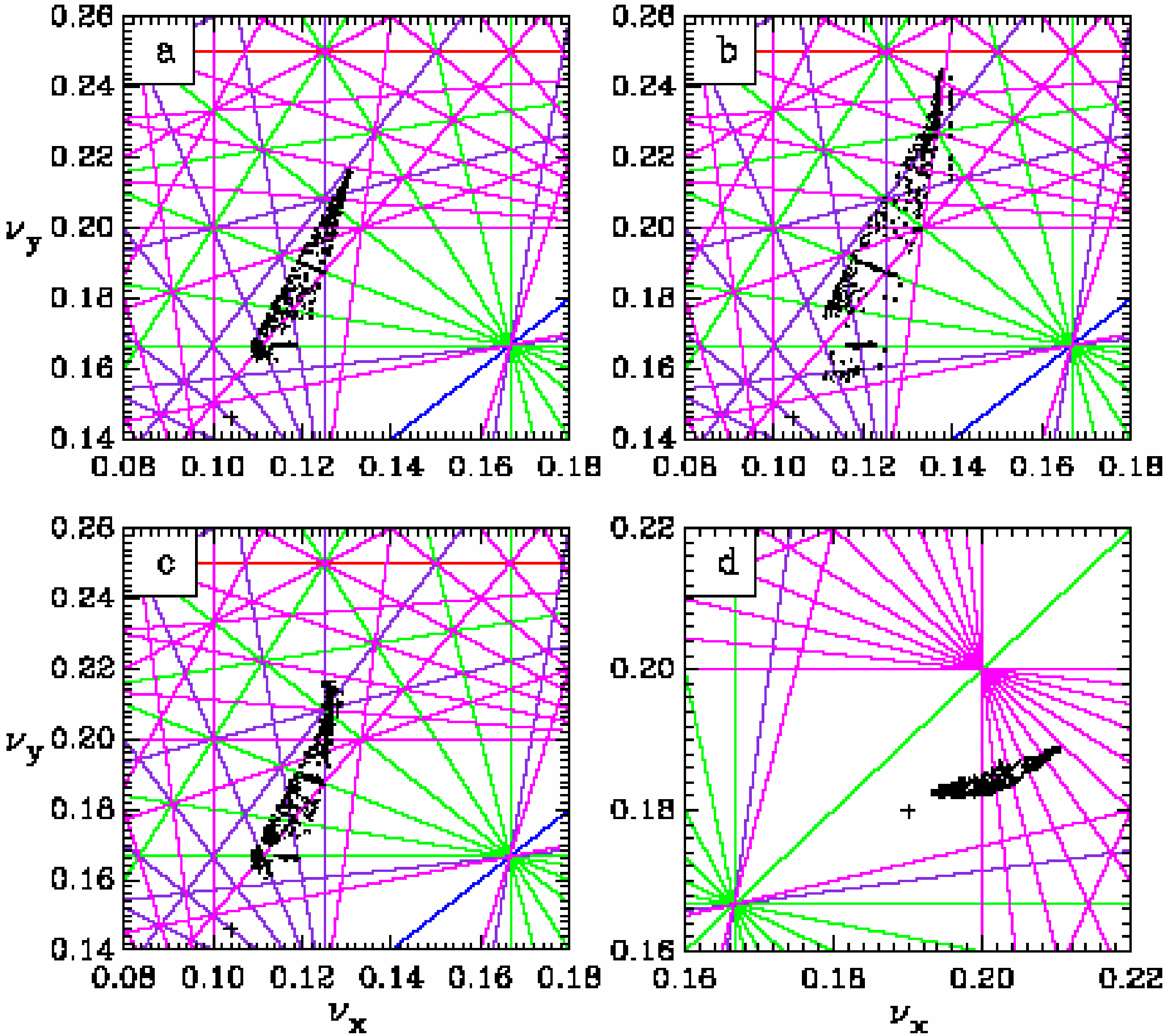


Case B:
N_p=N_{p0}
ξ_e =0.08

Case C:
N_p=1.25N_{p0}
ξ_e =0.01

Simulation verifies the ZDR e-beam b-b limit 0.08 is feasible.

Beam-beam tune spread



Tune spread for e

a) $N_e=N_{e0},N_p=N_{p0}$

6th order resonances

b) $N_e=N_{e0},N_p=1.5N_{p0}$

Two 6th and several 8thand 10th

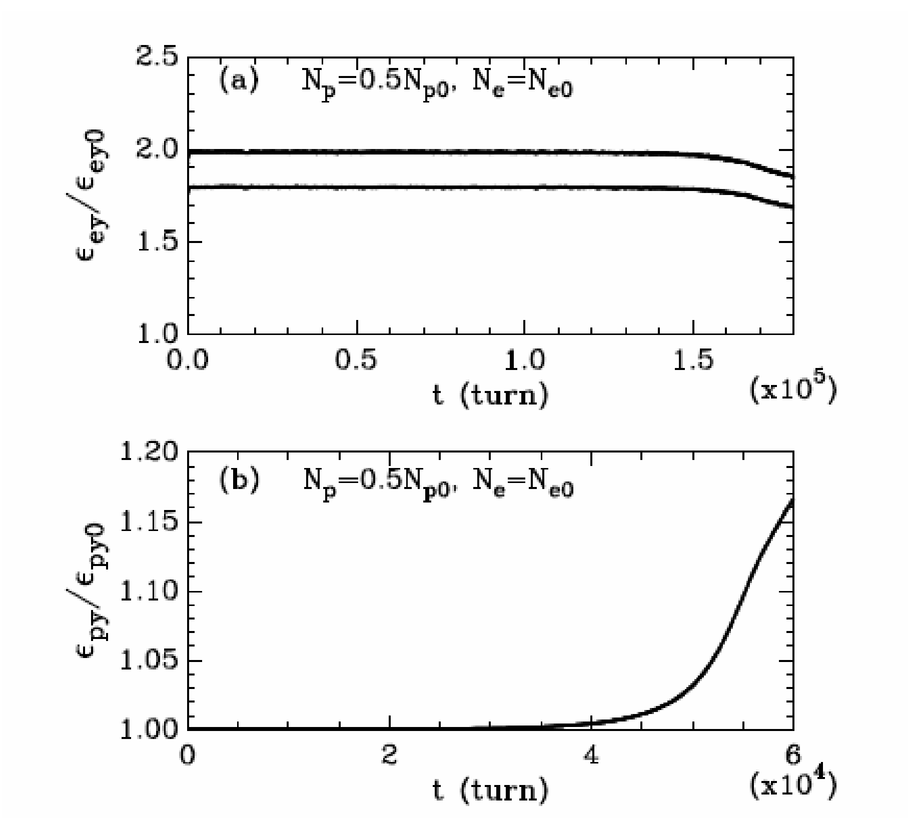
c) $N_e=3.5N_{e0},N_p=N_{p0}$

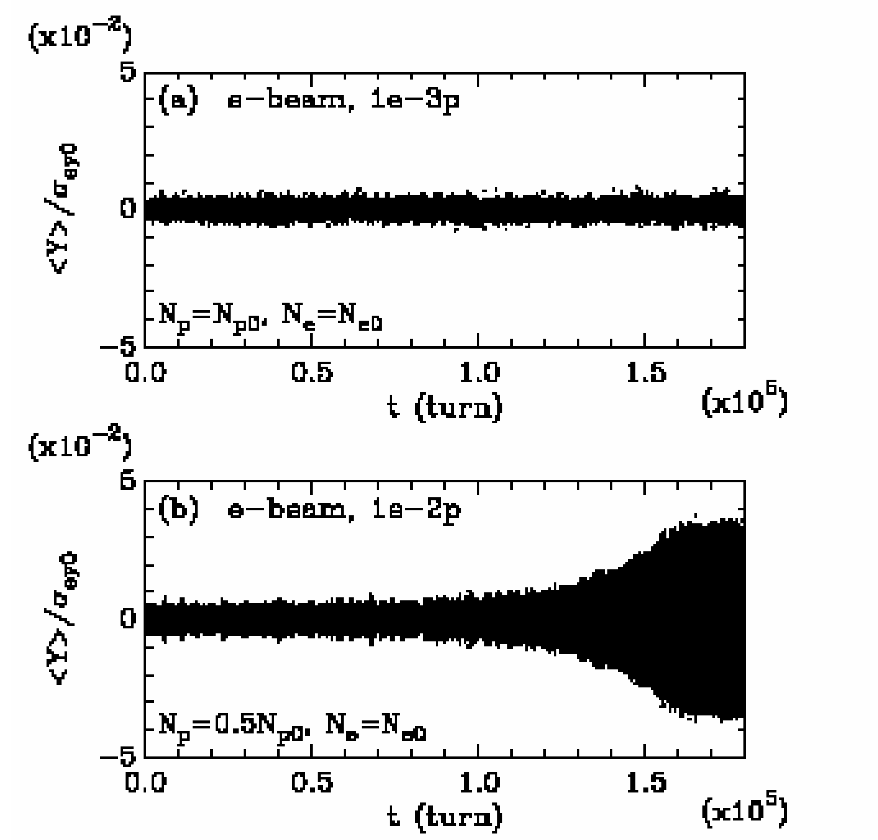
Tune spread for p

d) $N_e=3.5N_{e0},N_p=N_{p0}$

10 th resonances

Coherent b-b instability due to missing collisions





Vertical emittances with a missing p bunch.

e-beam (upper)

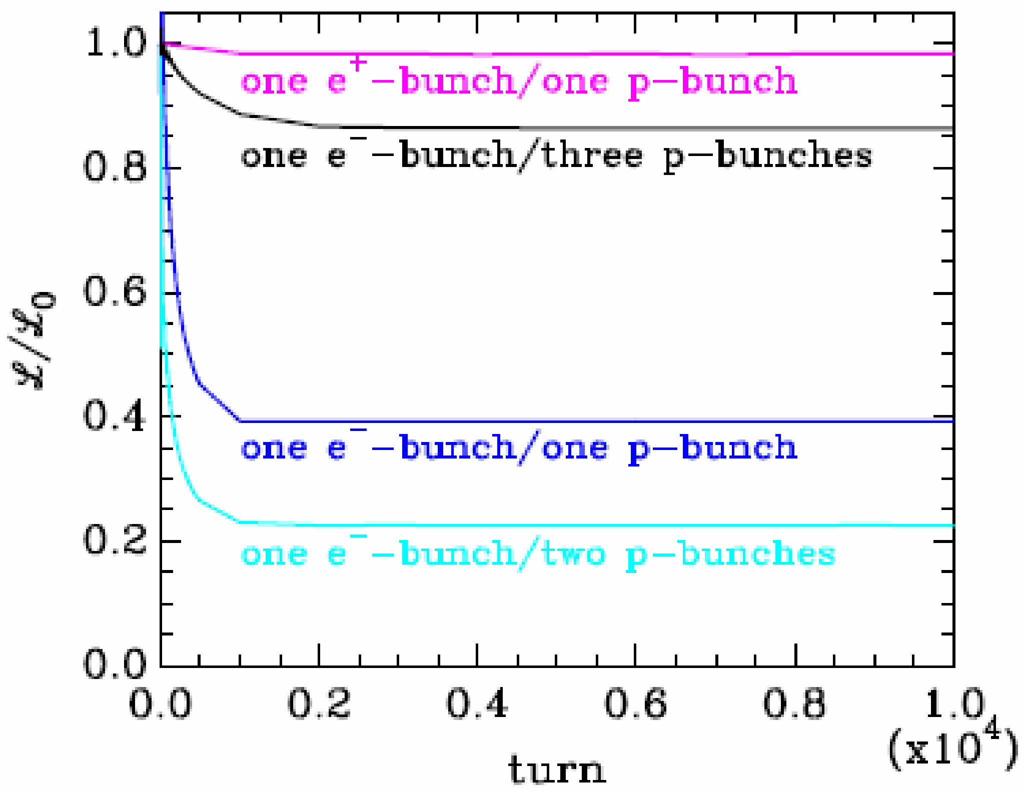
p-beam (bottom)

e beam vertical centroid

Stable (upper)

With a missing p bunch (bottom)

Luminosity Reduction due to beam-beam interactions



Working point search is important

Strong-strong simulation results

- For single IP
  - Beam-beam limit for lepton beam is $\xi_e \sim 0.08$.
  - Beam-beam limit for proton beam can be as high as $\xi_p \sim 0.016$.
  - Further investigation of working point is needed.

- Larger tune spread is the main cause of luminosity reductions. Effects of unequal circumference is not significant.

3. Collective effects

- General parameters
- Impedance budget and higher order mode (HOM) heating
- Single bunch instabilities
- Coupled bunch instabilities
- Ion related effects
- Electron cloud effects.

General Parameters

Energy (GeV)	5 - 10
Circumference (m)	1278
RF frequency (MHz)	478.6 or 506.6
RF voltage (MV)	5 - 25
Total current (A)	0.45– 1.12
Particles per bunch (10^{11})	1 - 2.5
Bunch spacing (m)	10.6
Momentum comp.	0.009/0.0026
Energy loss/turn (MeV)	0.72/11.7
Average beta (m)	~15
Bunch length (cm)	1~2

Impedance and HMO Heating

Impedance Budget

Components	Inductive impedance(ohm)	Loss factor (V/pC)
Cavities		~14/10
Resistive wall	2e-3	2.0
Masks	3e-2	2.0
Valves	6e-3	0.3
BPMs	1e-4	0.6
IR chambers	2e-3	2.0
Tapers	2e-2	2.0
Bellows	1e-2	2.0
Total	~0.06	~25/21

High Order Mode Heating

Loss factor(V/pC)	25
I = 450 mA	200 kW
I = 1000 mA	980 kW

Single bunch threshold (TMCI)

- TMCI (Transverse Mode-Coupling Instability)

  when imaginary part of transverse impedance couples the frequency of m=0 and m=-1 sidebands. It could be a single bunch current limit.

$$I_b = \frac{4(E/e)\nu_s}{\langle \mathrm{Im}(Z_\perp)\beta_\perp \rangle R} \frac{4\sqrt{\pi}}{3} \sigma_l$$

Typical threshold current is

~45mA at 10 GeV

~16 mA at 5 GeV

varies a little with synchrotron tune and bunch length.

Well above the design current, 3.9 mA(ZDR) or 10 mA (high luminosity operation).

Coupled bunch instabilities

- 120 bunches, 10.6 m bunch spacing
- Using the longitudinal and transverse modes in PEP-II nc and KEKB sc cavities, respectively, multi-bunch instability rise times are simulated.
- The fastest growth times are found to be:
  - longitudinal: ~228 ms
  - transverse: ~38 ms
- The damping time is 58 ms at 5 GeV.

- *Enhance Syn. Rad. Damping at low energy is in consideration.*
- *Also the existing feedback technology can handle it without difficulty.*

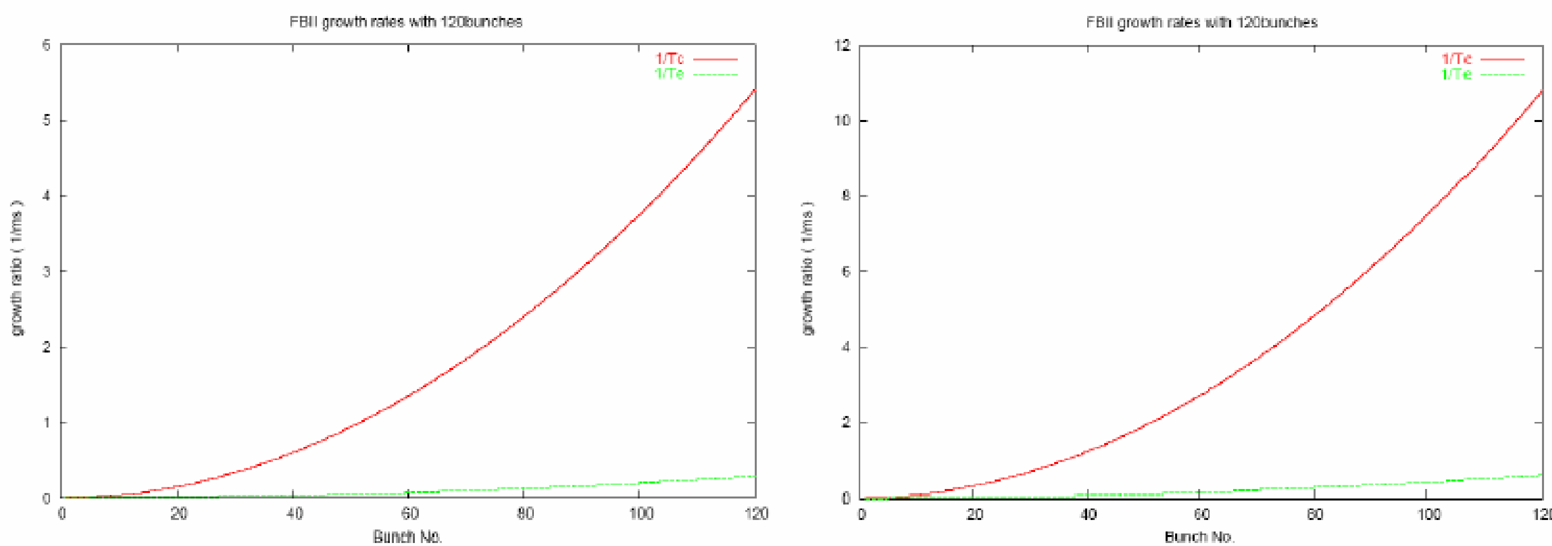
Fast Beam-Ion Instability (FBII)

For electron beam, due to high beam intensity, ions accumulate during a single passage of bunch train can cause transient instability.

linear model, T. Raubenheimer and F. Zimmermann (1995)

$$\frac{1}{\tau} = \frac{4 d_{gas} \sigma_{ion} \beta_y N_b^{3/2} n_b^2 r_e r_p^{1/2} L_{sep}^{1/2} c}{3\sqrt{3}\sigma_y^{3/2} \gamma (\sigma_x + \sigma_y)^{3/2} A^{1/2}}$$

For e-RHIC e-ring, FBII rise time at 1 A is about ~0.1 ms.
B-Factory type fast feedback system is necessary and sufficient.



10 GeV 5 GeV

Growth Rate at 1A current

red - linear model, green - taking into account of coherent frequency spread

Electron Cloud Effects (ECE)- Positron Beam

Observed effects:

pressure rise, beam-size blow-up, coupled-bunch instability …

Multi-bunch effect:

For coupled-bunch instability due to EC, if we assume that the density of the electron cloud is saturated, then the growth time can be estimated as :

$$\tau_{CB} = \frac{\gamma \omega_\beta h_x h_y L_{sep}}{2 r_e N_b c^2}$$

hx, hy: transverse dimensions of the vacuum chamber,
L is bunch spacing,
Nb is number of particles per bunch.

Assuming similar vacuum chamber dimensions to that of the existing lepton machines, the growth time is at the level of 1.0 ms in e+ operation.

Single bunch effect:

The electron cloud can also drive single bunch instability. Here we use treat it as a transverse mode-coupling instability. With a two-particle model, the threshold electron density of TMCI is

$$\rho_{e,threshold} \approx \frac{2\gamma\nu_s}{\pi\beta_y r_e C}$$

C is ring circumference. The threshold is about $1.2\text{x}10^{13}$ at 10 GeV and $0.6\text{x}10^{13}$ at 5 GeV, respectively. The preliminary simulation shows that *the electron cloud density in eRHIC lepton ring could approach this level if no precautionary measure is taken.* The above models may overestimate the effects in some extent.

The major cures include (KEKB, PEP II):

- a vacuum ante-chamber
- coating of the chamber with TiN or NEG
- installation of solenoid coils

Summary of Collective Effects

•Conventional impedance-related beam instabilities ***do not limit high current operation*** of the lepton ring

•The two-stream instabilities, mainly FBII and ECE, are major concerns. These two effects are comparable to those in the existing B-factories.

•Good engineering design and feedback can limit the instabilities to a similar or lower level than the B-factories at similar energy.

4. Low Energy Operation

Main difference:

Weak synchrotron damping, $P \propto \gamma^4$.

E=10 GeV, $\tau(x) \sim 7$ ms

E= 5 GeV, $\tau(x) \sim 59$ ms

Problems: Lower b-b tune shift limit, lower injection rate ~ 5 Hz and smaller emittance.

Beam-beam limit dependency on damping time

$$\xi_y^\infty = f[\lambda_d] = f[\frac{1}{f_{rev} \cdot \tau \cdot n_{IP}}] \qquad \text{beam} - \text{beam parameter before blow up}$$

λ_d: damping decrement, proportional to γ^3. R. Assmann, K. Cornelis, 2000

$\xi_y^\infty \propto \lambda_d^{\sim 0.3-0.4}$. from exp. data(LEP,Petra). Reduction»50% from 10 GeV to 5GeV

Radiation Enhancement:

•Damping wiggler: (CESR)

25m, field(peak)=2 Tesla. Prad.=(0.7+0.34)MW(0.5A), $\tau \sim 25$ ms,

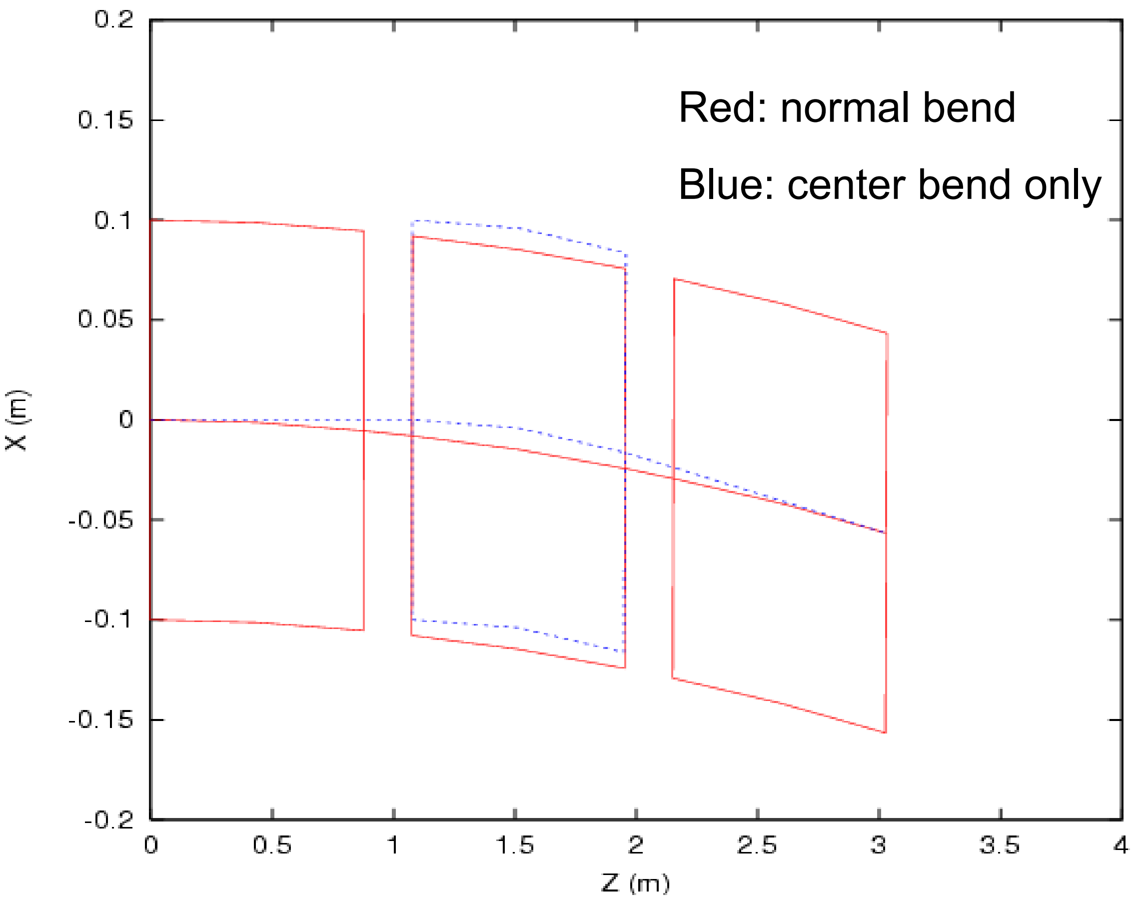
$\xi^\propto_y$ reduction ~30%, inj. Rate 13 Hz.

Concentrated rad. power, …? Impact on optics, beam dynamics?

•"Modular dipole": The 3m dipole => three sep. powered, ~0.9m dipoles. At 5 GeV only use the center one. Prad.=1MW.(0.45A).

Bmax≈7.1 KG. Arc magnet, vac. chamber complications.

Example of a modular dipole for radiation enhancement at 5 GeV



	All bends on	Center bend on only
ρ (m)	70.3m	23.4
B(KG) 5GeV	2.37	7.12
P (MW)	~0.35	~1.06
τ_x (msec)	~54.5	~18.1

ξ^{∞}_y reduction ~ 20%

(Compare to 10 GeV)

The length of the center bend can be different from the end ones to further enhance radiation at 5 GeV. Engineering and beam optics test can be done at Bates SHR (dipole : 3.59m).

5. Summary

- ZDR luminosity goals:

  e-p 10/250 GeV: L_0= 0.44x10^{33} cm^{-2}s^{-1}, …
- Post-ZDR study:
- New IR design, $\beta^*_{x,y}$ doubled , ***$L \rightarrow 0.5L_0$.***
- One IP, b-b simulation: $\xi_p \rightarrow$ ***0.015***, electron beam I_e limit doubled.

  ξ_p could be higher, work point scan required.

- Electron bean intensity does not limited by collective effects.
- Beam-beam limits can be maintained at low energy with reasonable engineering effort.
- **The ZDR luminosity goals can be attained.**

The Luminosity sheet

Single IP, New IR, Higher Luminosity Operation

		ZDR Design				Single IP, New IR, High e^- current operation			
		Electron	Proton	Electron	Au	Electron	Proton	Electron	Au
Energy E	[GeV]	10	250	10	100	10	250	10	100
$k=\varepsilon y/\varepsilon x$		0.18	1	0.14	1	0.18	1	0.15	1
$K\sigma=\sigma y/\sigma x$		0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
ε_n (ion)	[π mm mrad]		15.0		6.0		15.2		6.1
Emittancs εx	[nm.rad]	53.0	9.4	54.0	9.4	53.0	9.5	53.0	9.5
Emittancs εy	[nm.rad]	9.5	9.4	7.6	9.4	9.5	9.5	7.7	9.5
βx^*	[m]	0.19	1.08	0.19	1.08	0.39	2.16	0.39	2.16
βy^*	[m]	0.27	0.27	0.34	0.27	0.54	0.54	0.67	0.54
ξx		0.029	0.0065	0.022	0.0065	0.029	0.015	0.023	0.015
ξy		0.08	0.1000	0.08	0.0033	0.08	0.0075	0.08	0.0075
Particles/Bunch		1.00E+11	9.98E+10	9.88E+10	1.00E+09	2.33E+11	9.98E+10	2.32E+11	1.02E+09
Luminosity L	[$cm^{-2}s^{-1}$]		4.4E+32		4.4E+30		**5.1E+32**		**5.1E+30**